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APPLICATION OF ROLLING ELEMENT COASTDOWN TECHNIQUES TO THE DETERMINATION OF LUBRICANT PROPERTIES

By

S. F. Murray

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INTRODUCTION

The concept of elastohydrodynamic lubrication is known to depend on the non-Newtonian properties of the lubricant. In a previously reported study (1), a technique was described for studying this behavior by measuring the coast-down characteristics of lubricated, instrument-size ball bearings. Essentially, this was accomplished by lubricating the bearing with a small quantity of the test oil, driving the bearing up to a predetermined speed by means of an air turbine and recording the deceleration of the bearing after the air supply had been cut off.

The results of that study showed some significant experimental effects. It was found that the straight-chain dimethyl silicones gave exceptionally long coastdown times as compared with polyalkylene glycols or petroleum oils of comparable bulk viscosity, particularly in the high viscosity ranges (greater than 150 centistokes). A summary curve showing the coastdown times as a function of viscosity for homologous series of polyalkylene glycols and dimethyl silicones is shown as Figure 1. These data were taken from Reference 1. It was also found that, when a very shear-sensitive silicone oil was made by blending a 2×10^6 centistoke gum stock with a 0.65 centistoke dimer to form an oil with a bulk viscosity of 1000 centistokes at room temperature, the coastdown times obtained with this blend were comparable to the results obtained with a 10 centistoke dimethyl silicone. These data, which were also taken from Reference 1, are shown as Figure 2.

While the results of that study were very interesting, significant differences between oils were obtained only when oils of high viscosity were used. In the current program, an attempt has been made to improve this situation by using somewhat different experimental techniques. These included:

- (a) Heavier rotors to increase the inertia of the rotating members.
- (b) Radial, rather than thrust loaded bearings.
- (c) Elimination of windage losses by evacuating the system during the coastdown period

Major emphasis in this program has been to study oils of more reasonable bulk viscosity.

The objective of this portion of the program was to review and modify experimental techniques which could then be used to evaluate lubricant properties in later experimental work.

This report describes the results of this work to date.

TEST EQUIPMENT AND PROCEDURE

The equipment used for these tests consisted essentially of a horizontal rotor mounted on two size R-2 instrument bearings. A steel gear was pressed on the rotor to act as a turbine wheel. Stainless steel tubing was used to direct a stream of compressed air around the periphery of the gear, thus driving the rotor. Figures 3 and 4 are photographs of this test equipment.

This rotor had a series of removable weights which allowed changes in the bearing load. The loads were as follows:

Number of weights	Total Load	Load per Bearing
All weights (6)	444 grams	222 grams
Four weights	334 "	167 "
Two weights	218 "	109 "
No weights (shaft only)	112 "	56 "

Speed was measured by means of a magnetic pickup which was connected to an electronic tachometer with a recorder on the output side.

It should also be noted that this equipment was run on its side in a few of the tests. This applied all of the load, as a thrust load, to one bearing while the other bearing acted only as a guide.

To decrease the windage losses during coastdown, this bearing test assembly was enclosed in a bell jar. The bell jar was mounted on a metal base through which the necessary inlet and outlet piping was attached. A series of solenoid valves were used to permit rapid switching. Compressed air was brought into the bell jar through a normally open solenoid valve. A mechanical rough pump exhausted a line which was sealed by a normally closed solenoid valve. When the test unit had been brought up to the desired speed, a switch was used to energize these valves. This shut off the supply of compressed air and simultaneously opened the valve to the vacuum side. In Figure 5, a typical coastdown curve is plotted, showing the change in ambient pressure, with time, inside the bell jar.

The bearings used in these tests were deep groove, 52100 steel, size R-2 instrument bearings with a one piece, mild steel, snap retainer.

These bearings were cleaned in Soxhlet extraction columns, first with benzene and then with alcohol. Lubricant was applied by flooding the bearings. To remove excess, the bearings were then centrifuged for 30 seconds on each side at 100 g, then mounted on the shaft and the test was assembled.

TEST RESULTS AND DISCUSSION

1. SAE IOW-30 Petroleum Oil

As a preliminary check on the operating characteristics of the equipment, a series of tests were run under various loads, using a multigrade SAE IOW-30 petroleum oil as the lubricant. Tests were run in air and in vacuum. In Table 1, a summary of all of the test data is given. The results of the IOW-30 tests are shown in Figure 6.

Since load is increased by the addition of disks to the rotor, an increase in load is accompanied by increases in inertia and windage loss (for air operation). The windage and inertia effects would be expected to be linear with area and mass respectively.

If one assumed that bearing friction was linear with load, then the load and inertia effects would negate each other insofar as coastdown time was concerned, and windage would appear to be the dominant effect. The results clearly indicate that this was not the case, since coastdown time increased with load in air and in vacuum. Comparison of air and vacuum results show greater variations in coastdown time at higher loads. However, the degree of variation is much smaller than predicted by the area change.

The implication by a superficial review was that the bearing friction varied inversely with load. However, since this conclusion would be clearly a paradox, it was felt that the data should be completely analyzed.

If the 445 gm load is used as a datum, the equation of motion is

$$I_1 \frac{dw}{dt} = T_f + T_w \tag{1}$$

where

I_1 = mass moment of inertia of the 445 gm. rotor.

T_f = bearing frictional torque.

T_w = windage torque.

This can be rewritten as

$$\frac{dw}{dt} = \frac{T_f}{I_1} + \frac{T_w}{I_1} \tag{2}$$

A dimensionless speed and time are defined as

$$\Omega = w/w_o$$

$$\tau = t/t_1$$

Equation (2) can be rewritten as

$$\frac{d\Omega}{d\tau} = \frac{d\,(w/w_o)}{d\,(t/t_1)} = \frac{T_f\,t_1}{I_1\,w_o} + \frac{T_w\,t_1}{I_1\,w_o} \tag{3}$$

Equation (3) is dimensionless and a dimensionless friction and windage are defined by

$$\phi_f = \frac{T_f\,t_1}{I_1\,w_o}$$

$$\phi_w = \frac{T_w\,t_1}{I_1\,w_o}$$

Equation (3) now becomes

$$\frac{d\Omega}{d\tau} = \phi_f + \phi_w \tag{4}$$

For the runs in vacuo, $\phi_w = 0$ and

$$\frac{d\Omega}{d\tau} = \phi_f \tag{5}$$

In analyzing the data, τ and w_o are referred to the recorder chart.

τ = chart time units

w_o = initial speed at the beginning of coastdown.

Once Ω versus τ is obtained, $d\Omega/d\tau$ may be obtained graphically. With $d\Omega/d\tau$, the quantity $(\Phi_f + \Phi_w)$ is defined for air operation and Φ_f defined from vacuum operation.

For any other rotor configuration of inertia I_2, the dimensionless relationship is

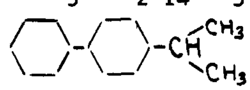
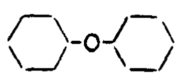
$$\frac{d\Omega}{d\tau} = \frac{I_1}{I_2} (\Phi_f + \Phi_w) \tag{6}$$

Since lubricant effects are being considered, the frictional behavior (Φ_f) is desired as a function of speed (Ω). Figure 7 shows the data for the 445 gram and 230 gram rotor. This shows Φ_f as a function of Ω.

The conclusion is that little or no variation was detected and that the apparent anomaly was induced by the change in inertia. It also demonstrated that future efforts should consider other loading means.

2. Pure Hydrocarbons

This was a series of tests on pure hydrocarbon compounds having a known chemical structure. These compounds, their chemical structures and room temperature bulk viscosities were as follows:

Compound	Structure	Viscosity
1. Hexadecane	$CH_3\ (CH_2)_{14}\ CH_3$	4.4 ctsks at 75°F
2. Monoisopropylbiphenyl		7.94
3. Phenylether		3.66 at 85°F

The hexadecane is a long, straight-chain hydrocarbon with a structure favorable to close packing. Monoisopropylbiphenyl has only one less carbon atom than hexadecane, but consists of two phenyl groups with a short chain hydrocarbon attached to one of the rings. The structure is fairly rigid. The phenyl ether is similar to the monoisopropylbiphenyl, but the presence of the ether linkage permits free rotation of the phenyl groups as contrasted to the rigid geometry of the monoisopropylbiphenyl.

As shown in the summary in Table 1, the monoisopropylbiphenyl and the phenyl ether had identical coastdown times while the hexadecane gave a slightly longer coastdown. It is doubtful if these results can be considered significant because of the low viscosities of these compounds, although it is interesting that the hexadecane was slightly better than the monoisopropylbiphenyl, indicating that a variation in viscosity could be measured even in this low range. The phenyl ether was probably a poor choice for these tests because this compound melts at 26-28^{o}C and it is difficult to know what the exact temperature of this oil was during the test. A small variation in temperature could have made a large difference in viscosity and this could distort the test results.

3. Ucon Oils

The results obtained with a series of Ucon oils of different viscosities are shown in Figure 8. For comparison, the data obtained in Reference 1 are also plotted, but it should be noted that the test conditions were different, particularly because of the rotor inertias and masses.

The general shapes of the curves are similar, but the radial loaded bearings used in these tests do not show a deviation from a straight line in the plot of viscosity vs. coastdown time until the bulk viscosity is less than 75 centistokes, while the thrust loaded bearings used in Reference 1 show a marked change below 250 centistokes. This difference can probably be attributed to the higher inertia of the present rotor. As the viscosity of the test oils is reduced, the spread in coastdown times between the air and the vacuum tests gradually increases. This indicates that the windage was becoming the dominant factor.

4. Glycerol-Water Mixtures

The compressibility of glycerol is very low as compared to most petroleum lubricants. This appears to be associated with the presence of strongly polar hydroxy groups which provide strong cohesive forces between the molecules (2). Since certain other fluids such as the silicones have high compressibility and very weak cohesive forces, it seemed worthwhile to evaluate glycerol and a couple of glycerol-water mixtures in order to see if some unusual results would be obtained. The results are shown in Figure 9.

Using 100% Glycerol as the lubricant, there is remarkedly little difference between the total coastdown in air and in vacuum. Referring to the data in Table 1, note that the differences are in the high end of the coastdown curve. The lower ends of the curve, from 6400 rpm to stop, are identical, This is rather unusual since other oils showed most of the variations in the low end of the curve.

As the glycerol is diluted with water, the spread between the vacuum and the air tests becomes greater and more typical coastdown behavior is observed. At present, we have no explanation worked out for these results. However, it should be noted that, as the glycerol is diluted with water, the cohesion between molecules seems to decrease and presumably the compressibility increases.

This appears to be an interesting avenue for further work.

5. Experimental Esso Petroleum Oils

Since the data of Reference 1 had indicated that shear-viscosity behavior was an important parameter, particularly with the silicone oils, two samples of experimental petroleum oils were obtained for evaluation. Both of these lubricants were shear-sensitive, one more so than the other, although the differences were actually not too great. In Table 2, the effect of shear rate on viscosity is shown for each of these samples.

For comparison, Nujol, which is a highly Newtonian oil, was also obtained. To obtain maximum shear rates, the first set of coastdown curves were taken from 42,800 rpm to stop. The following results were obtained:

Coastdown Time (42,800 rpm to stop)

Oil	Bulk Viscosity at 75°F	Environment	Load-grams	Coastdown Time Total	1st half	2nd half
Esso-11	147 ctsks	Air	218	220 sec.	15 sec.	205 sec.
Esso- 5	159 "	"	"	207.5 "	12.5 "	195 "
Nujol	192 "	"	"	184.4 "	12.5 "	171.9 "

Comparing the results obtained with these three oils, it appears that the small differences were probably due to differences in bulk viscosity rather than shear viscosity characteristics.

Since one of these oils (-11) was supposed to show a greater permanent loss in viscosity than the other (-5), a series of tests were run with one charge of lubricant to see if repeated cycles would give a larger change with the more shear-sensitive oil. The Esso-11 oil gave the following results.

Coastdown Time (12,800 rpm to stop) Esso-11 oil

Environment	Load-grams	Coastdown Time total	1st half	2nd half
Air	218	138.8	23.1	115.7 sec.
Vacuum	"	174.4	33.8	140.6
Air	"	152.5	26.3	126.2
Vacuum	"	193.1	40	153.1

Note that some increase in coastdown time was obtained with each succeeding test. These differences were greater than one would expect for a stable oil and, although not large, they should be considered as being significant.

The Esso-5 oil gave the following results:

Coastdown Time (12,800 rpm to stop) Esso-5 oil

Environment	Load-grams	Coastdown Time total	1st half	2nd half
Air	218	141.3	24.4	116.9 sec.
Vacuum	"	170	35.6	134.4
Air	"	147.5	26.3	121.2
Vacuum	"	181.3	37.5	143.8

Although this oil also showed an increase in coastdown time with each succeeding test, the differences were about half of the changes obtained with the -11 oil.

Two tests were also run on these oils using the full load, but here, the differences were extremely small and in the wrong order. These data are listed in Table 1.

The results of these tests indicate that very careful experimentation will be required to show significant differences between oils for this bulk viscosity and shear sensitivity. The "series" tests where the bearing was lubricated once and then run through a series of coastdown tests looked promising. A better method would be to run the bearing at some steady speed for a period of time and then measure coastdown.

6. Silicone Oils

In Reference 1, it was shown that the high viscosity silicone oils were extremely sensitive to high rates of shear. The data plotted in Figures 1 and 2 illustrate this effect. In this program, the behavior of lower viscosity silicones was investigated. A straight chain dimethyl silicone with a bulk viscosity of 108 centistokes was compared with a "compressible" silicone, XF 1037, which was a blend of a 2×10^6 centistoke gum stock with a 0.65 centistoke dimer to form a fluid with a bulk viscosity of 106 centistokes. This latter oil is very shear-sensitive.

Tests were run in air and in vacuum with a radial load of 444 grams. The test data, which are listed in Table 1, gave extremely small differences which were in the wrong order, except for the first half coastdowns of the vacuum tests. These showed longer coastdown times for the shear-sensitive silicone.

To determine if a thrust loaded bearing would give different results, the test stand was rotated 90° so that one bearing was carrying all of the load, as a thrust load, and the other bearing was acting as a guide. With a thrust load of 218 grams, the shear-sensitive silicone blend gave a 10% longer coastdown than the straight silicone. Although this increase was significant, it was not as great as had been anticipated. Repeating this test with a 444 gram thrust load, the results were inverted. The shear-sensitive silicone gave a shorter total coastdown, although the first half of the coastdown curve, where the shear rate was highest, was longer for this oil. Since heavier loads appeared to be a step in the wrong direction, tests were then made with a thrust load of 112 grams but the shear-sensitive oil still gave a shorter coastdown time.

It was finally determined that the technique which was being used to centrifuge the bearings was the cause of these difficulties. The shear-sensitive silicone was blended with a silicone dimer which is a light, volatile oil. Centrifuging the bearings was either discarding or evaporating the dimer, thus leaving a more viscous silicone blend in the bearing.

To demonstrate this effect, another test was run with a thrust load of 112 grams, but this time the bearings were centrifuged for only 10 seconds on one side. This reversed the results of the previous test.

CONCLUSIONS

Although the results of these tests still leave many questions unanswered, a great deal of information on experimental techniques has been obtained. For example:

1. Increasing the inertia of the rotor does not contribute to the accuracy of the data. In fact, this appears to mask the differences between lubricants.

2. Use of radial rather than thrust-loaded bearings makes little difference in the results obtained. The choice of load direction is more a matter of convenience than anything else.

3. The use of a vacuum technique to decrease windage losses appears to be a good step, even if it does nothing but increase the coastdown time. More work is required to determine what other effects this also produces.

4. Analytical techniques have been developed to provide tools which can be used to interpret these results in terms of dimensionless parameters.

5. It is possible to use this technique for evaluating the performance of lubricants in the practical viscosity range rather than with high viscosity oils. However, the tests must be very carefully planned and a sufficient number must be made to permit some statistical analyses to be made.

6. It would be desirable to find a better loading means. Spring loading would be a possible choice.

REFERENCES

1. "Effect of Lubricant Properties on the Coastdown Characteristics of Instrument Bearings," P. Lewis and S.F. Murray. Lubrication Engineering. January 1962.

2. "Physical Chemistry of Lubricating Oils," A. Bondi, Reinhold Publishing Corp., N. Y., 1951.

TABLE 1 - SUMMARY OF COASTDOWN TEST RESULTS FOR VARIOUS LUBRICANTS

LUBRICANT	BULK VISCOSITY AT 75° F (MEASURED)	ENVIRONMENT	LOAD	COASTDOWN TIME (12,800 rpm to stop)		
				TOTAL	FIRST HALF	SECOND HALF
1. SAE IOW-30 "	85 ctsks	Air Vacuum	444 grams " "	362.5 sec. 610 "	62.5 sec. 150 "	330 sec. 460 "
" "	-	Air Vacuum	334 " " "	290 " 490 "	50 " 120 "	240 " 320 "
"	-	Air Vacuum	218 " 218 "	205 " 320 "	35 " 75 "	170 " 245 "
2. Hexadecane	4.4 ctsks	Air Vacuum	444 grams " "	360 sec. 555 "	60 sec. 155 "	300 sec. 400 "
3. Monoisopropylbiphenyl	7.94 ctsks	Air Vacuum	444 grams " "	350 sec. 510 "	60 sec. 130 "	290 sec. 380 "
4. Phenyl ether	3.66 ctsks*	Air	444 grams	350 sec.	60 sec.	290 sec.
5. Ucon Oils 50HB100	36.1 ctsks	Air Vacuum	444 " " "	332.5 sec. 490 "	60 sec. 132.5 "	272.5 sec. 357.5 "
50HB170	70 ctsks	Air Vacuum	" " " "	320 sec. 472.5 "	58 sec. 130 "	262 sec. 342.5 "

*at 85°F

TABLE 1 (CONTINUED)

LUBRICANT	BULK VISCOSITY AT 75°F (MEASURED)	ENVIRONMENT	LOAD	COASTDOWN TIME (12,800 rpm to stop)		
				TOTAL	FIRST HALF	SECOND HALF
50HB280X	115 ctsks	Air Vacuum	444 grams " "	300 sec. 430 "	58 " 112.5 sec.	242 " 317.5 sec.
50HB660	298 ctsks	Air Vacuum	" " " "	287.5 sec. 410 "	55 sec. 105 "	232.5 sec. 305 "
50HB20000	946 ctsks	Air Vacuum	" " " "	240 sec. 332.5 "	47.5 sec. 87.5 "	192.5 sec. 245 "
6. Glycerol-Water Mixtures 100% Glycerol	1190 ctsks at 68°F (Handbook data)	Air Vacuum	" " " "	197.5 sec. 217 "	42.5 sec. 60 "	155 sec. 155 "
50% Glycerol 50% Glycerol	Not meas.	Air Vacuum	" " " "	260 sec. 335 "	45 sec. 77.5 "	215 sec. 257.5 "
10% Glycerol 90% Glycerol	"	Air Vacuum	" " " "	302.5 sec. 405 "	55 sec. 105 "	247.5 sec. 300 "
7. Esso Oils Esso -11(a) Esso - 5(a) Nujol (a)	 147 ctsks 159 " 192 "	 Air " "	 218 grams " " " "	 220 sec. 207.5 " 184.4 "	 15 sec. 12.5 " 12.5 "	 205 sec. 195 " 171.9 "
Esso -11	-	Air Vacuum Air Vacuum	218 grams " " " " " "	138.8 sec. 174.4 " 152.5 " 193.1 "	23.1 sec. 33.8 " 26.3 " 40 "	115.7 sec. 140.6 " 126.2 " 153.1 "

(a) Coastdown from 42,800 rpm to 0

TABLE 1 (CONCLUDED)

LUBRICANT	BULK VISCOSITY AT 75°F (MEASURED	ENVIRONMENT	LOAD	COASTDOWN TIME (12,800 rpm to stop)		
				TOTAL	FIRST HALF	SECOND HALF
Esso -5	-	Air	218 grams	141.3 sec.	24.4 sec.	116.9 sec.
		Vacuum	" "	170 "	35.6 "	134.4 "
		Air	" "	147.5 "	26.3 "	121.2 "
		Vacuum	" "	181.3 "	37.5 "	143.8 "
Esso -11	-	Air	444 grams	305 sec.	57.5 sec.	247.5 sec.
Esso - 5	-	Air	" "	310 "	57.5 "	252.5 "
8. Silicone Oils						
Dimethyl Silicone (100 ctsks)	108.1 ctsks	Air	" "	335 sec.	60 sec.	275 sec.
		Vacuum	" "	463 "	127.5 "	337.5 "
Compressible Silicone XF 1037	105.1 ctsks	Air	" "	330 sec.	60 sec.	270 sec.
		Vacuum	" "	462.5 "	140 "	322.5 "
XF-1037	-	Air, Full Centrifuge	218 g (a)	197.5 sec.	35 sec.	162.5 sec.
Silicone(100cs)	-	"	218 g (a)	177.5 "	32.5 "	145 "
XF-1037	-	"	444 g (a)	275 "	55 "	220 "
Silicone(100cs)	-	"	444 g (a)	312.5 "	52.5 "	260 "
Dimethyl Silicone(100cs)	-	Air, Full Centrifuge	112 g (a)	70 sec.	15 sec.	55 sec.
XF 1037 Silicone	-	Air, Full Centrifuge	112 g (a)	60 sec.	15 sec.	45 sec.
Dimethyl Silicone	-	Air, 10 sec. Centrifuge	112 g (a)	70 sec.	15 sec.	55 sec.
XF1037 Silicone	-	"	112 g (a)	80 sec.	17.5 sec.	62.5 sec.

(a) Thrust Load on one bearing.

TABLE 2 - EFFECT OF SHEAR RATE ON VISCOSITY OF EXPERIMENTAL PETROLEUM OILS

Esso Oil -5 Temp. 25°C			Esso Oil -11 Temp. 25°C		
Rate of shear (sec^{-1})	Stress (dyn/cm^2)	Poises	Rate of shear (sec^{-1})	Stress (dyn/cm^2)	Poises
0		1.10	0		1.10
7.5×10^3	8.27×10^3	1.09			
1.0×10^4	1.09×10^4	1.10			
1.5×10^4	1.65×10^4	1.10			
2.5×10^4	2.60×10^4	1.04			
5.0×10^4	4.64×10^4	0.93	5.0×10^4	5.0×10^4	1.0
7.5×10^4	6.84×10^4	1.04			
1.0×10^5	9.31×10^4	0.93	1.0×10^5	8.19×10^4	0.82
1.5×10^5	1.31×10^5	0.88	1.5×10^5	1.10×10^5	0.73
2.5×10^5	2.02×10^5	0.81	2.5×10^5	1.58×10^5	0.63
5.0×10^5	3.39×10^5	0.68	3.5×10^5	1.98×10^5	0.57
7.5×10^5	4.67×10^5	0.62	5.0×10^5	2.62×10^5	0.52
1.0×10^6	5.78×10^5	0.58	1.0×10^6	3.83×10^5	0.38
∞		0.347	∞		0.347

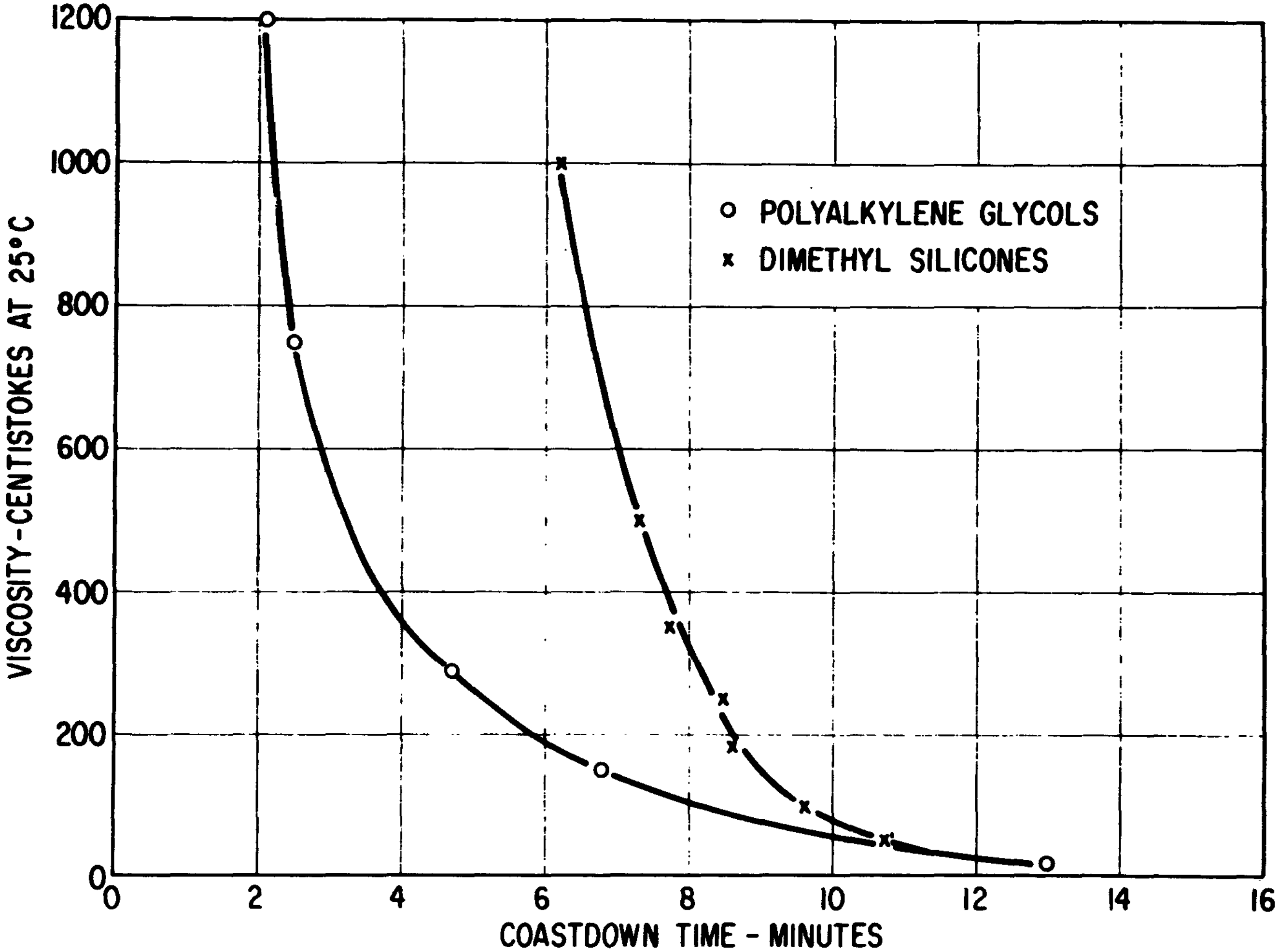


FIG. 1 COASTDOWN TIME AS A FUNCTION OF VISCOSITY

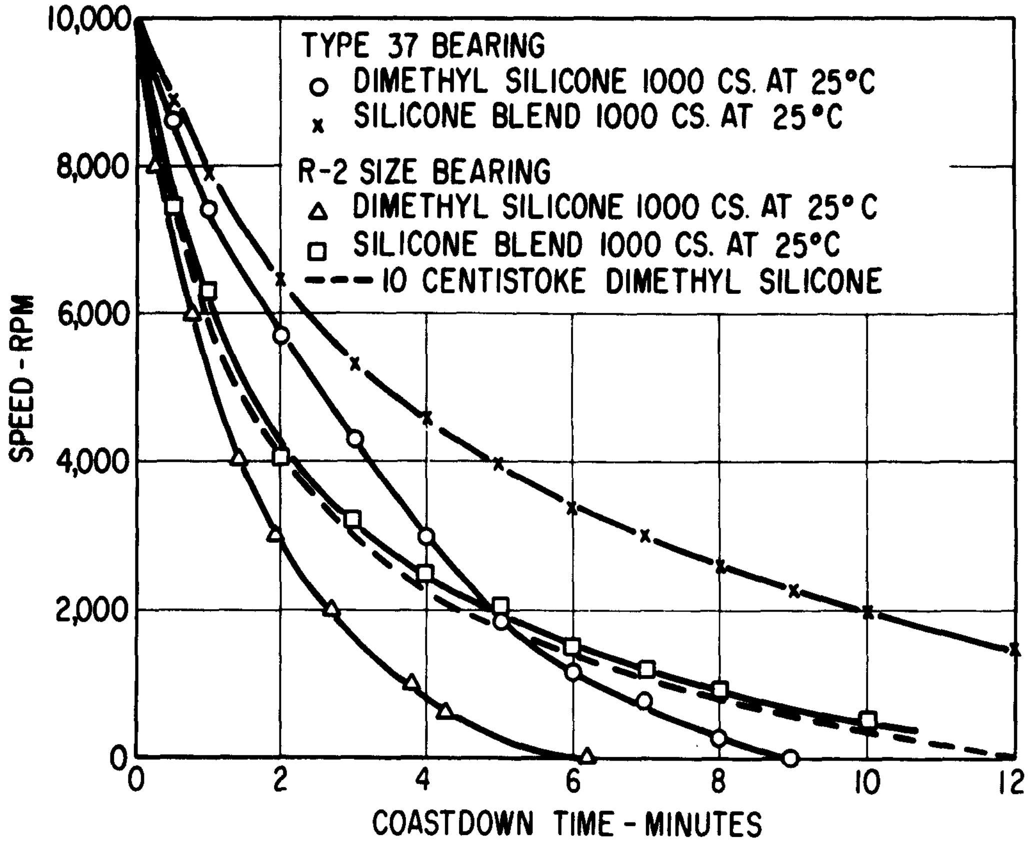


FIG. 2 EFFECT OF SHEAR - VISCOSITY CHARACTERISTICS ON COASTDOWN TIME

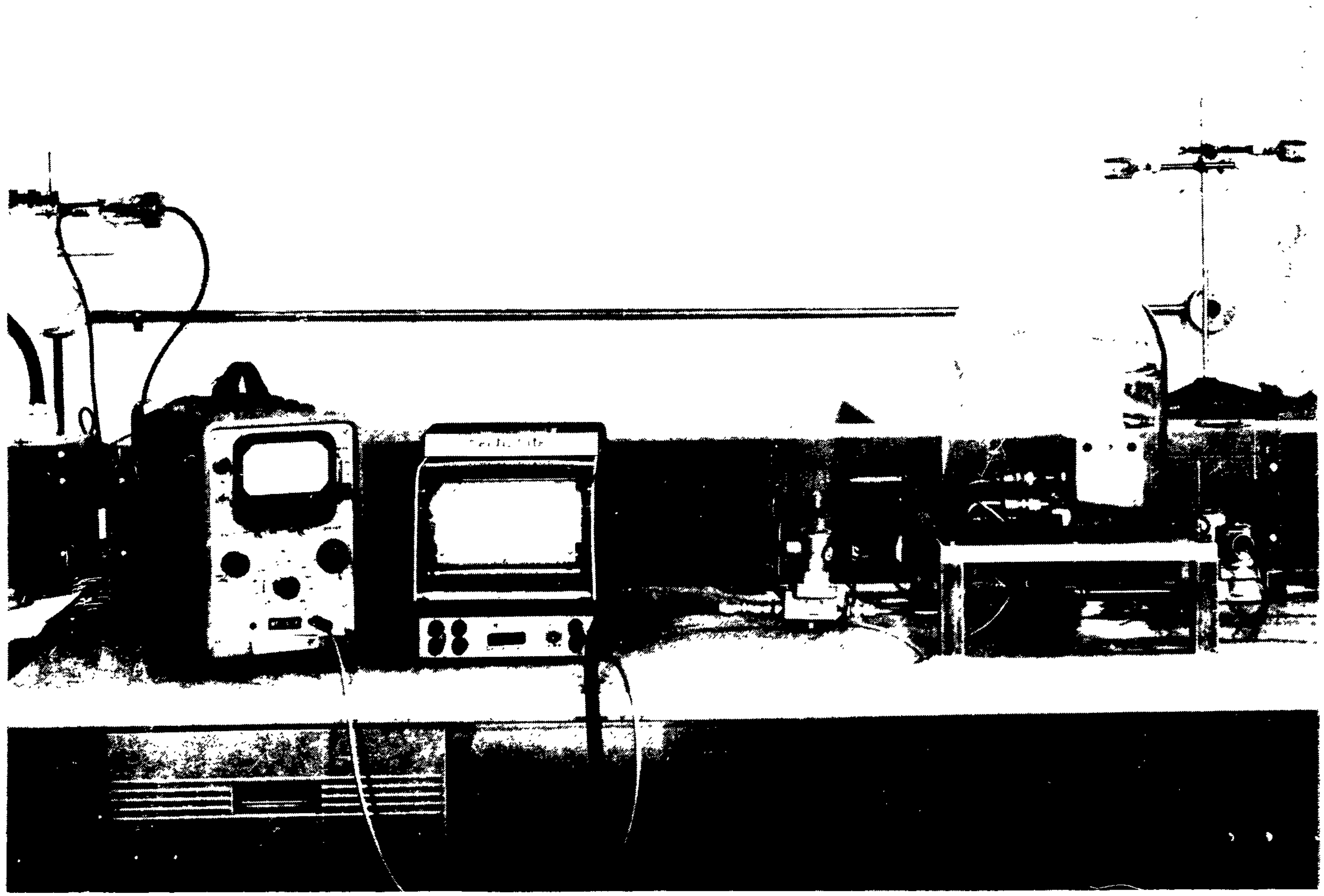


Fig. 3 Over-all View of Coast-down Apparatus

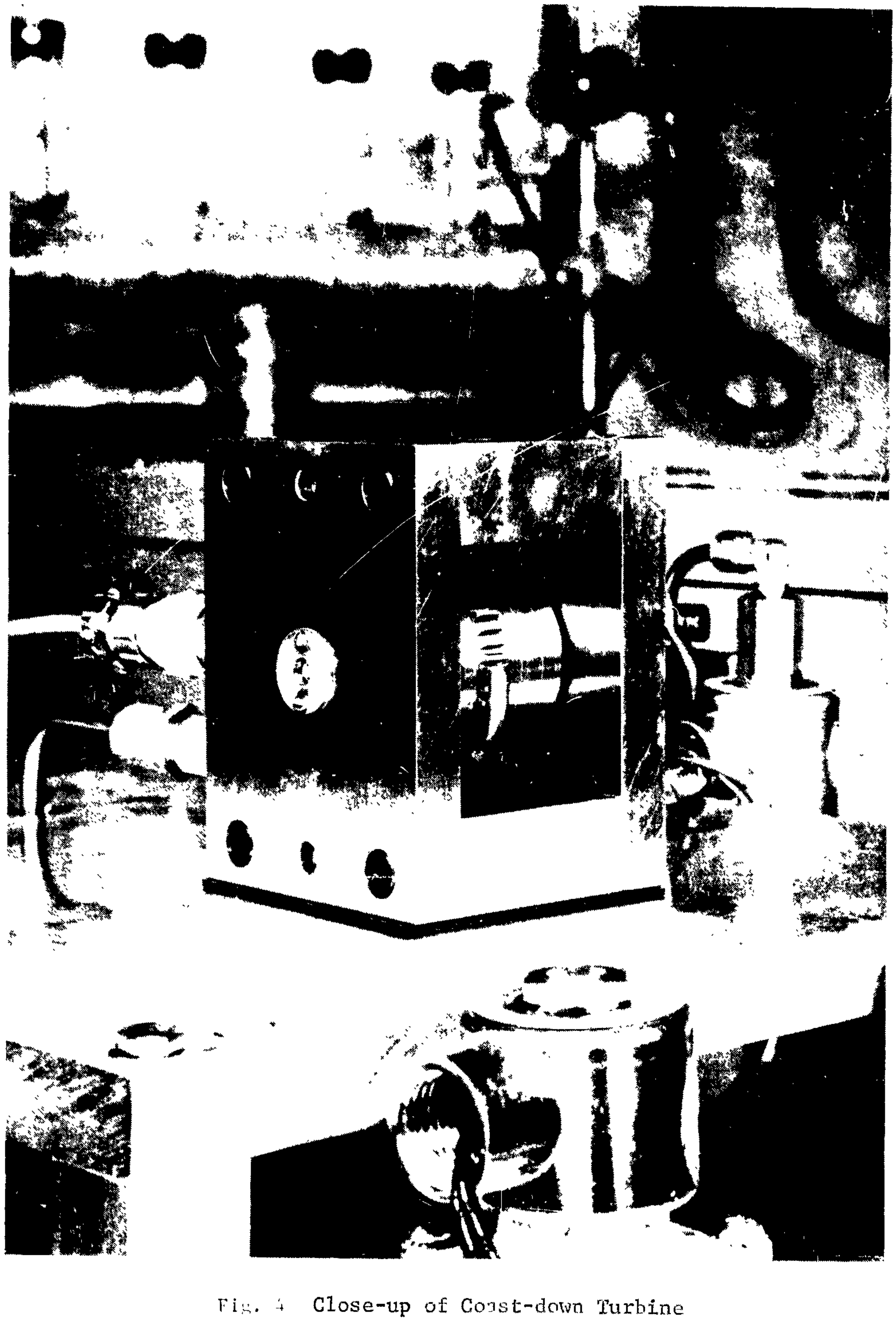


Fig. 4 Close-up of Coast-down Turbine

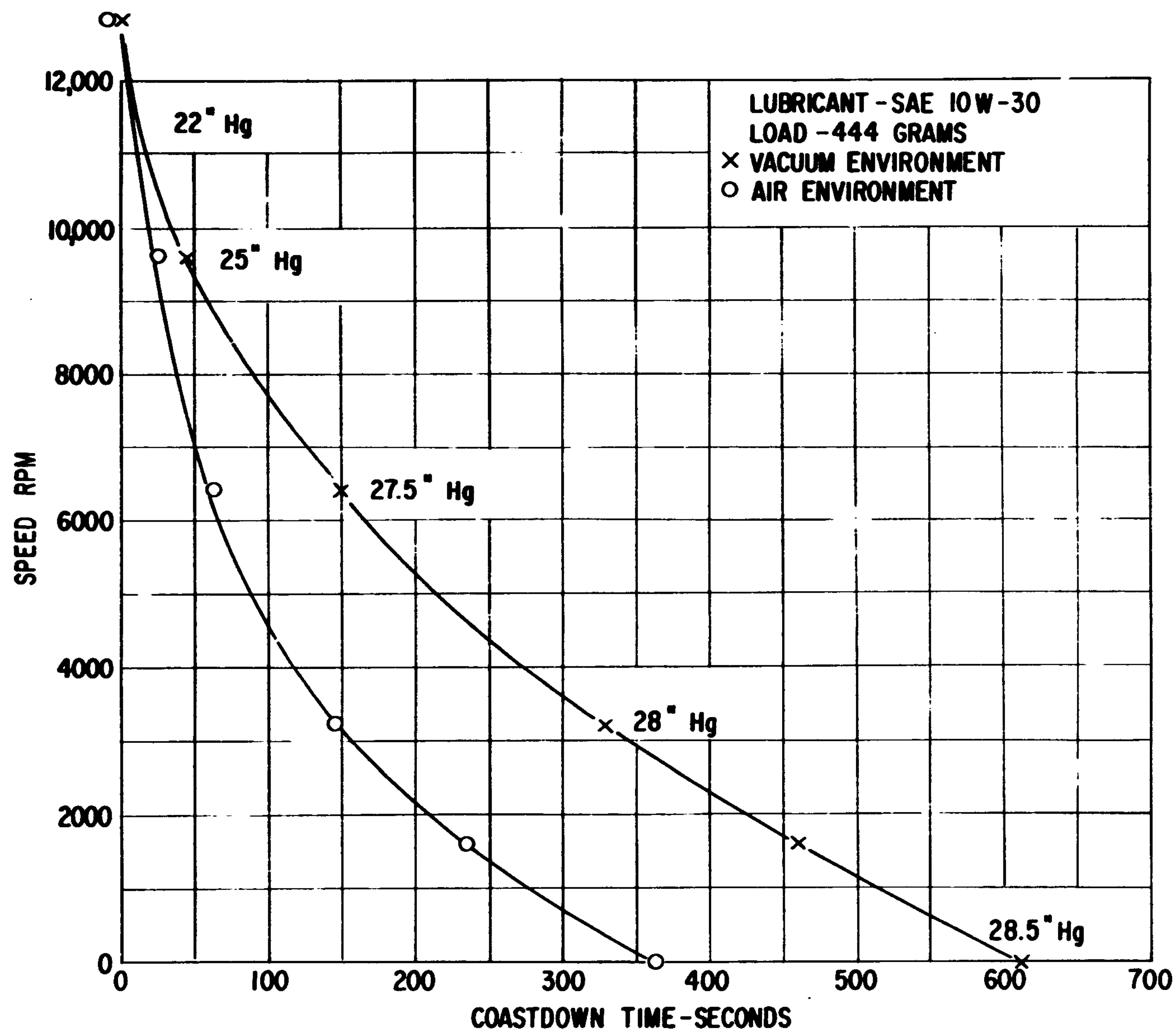


FIG. 5 TYPICAL COASTDOWN CURVES SHOWING EFFECT AND EXTENT OF VACUUM ON COASTDOWN TIME

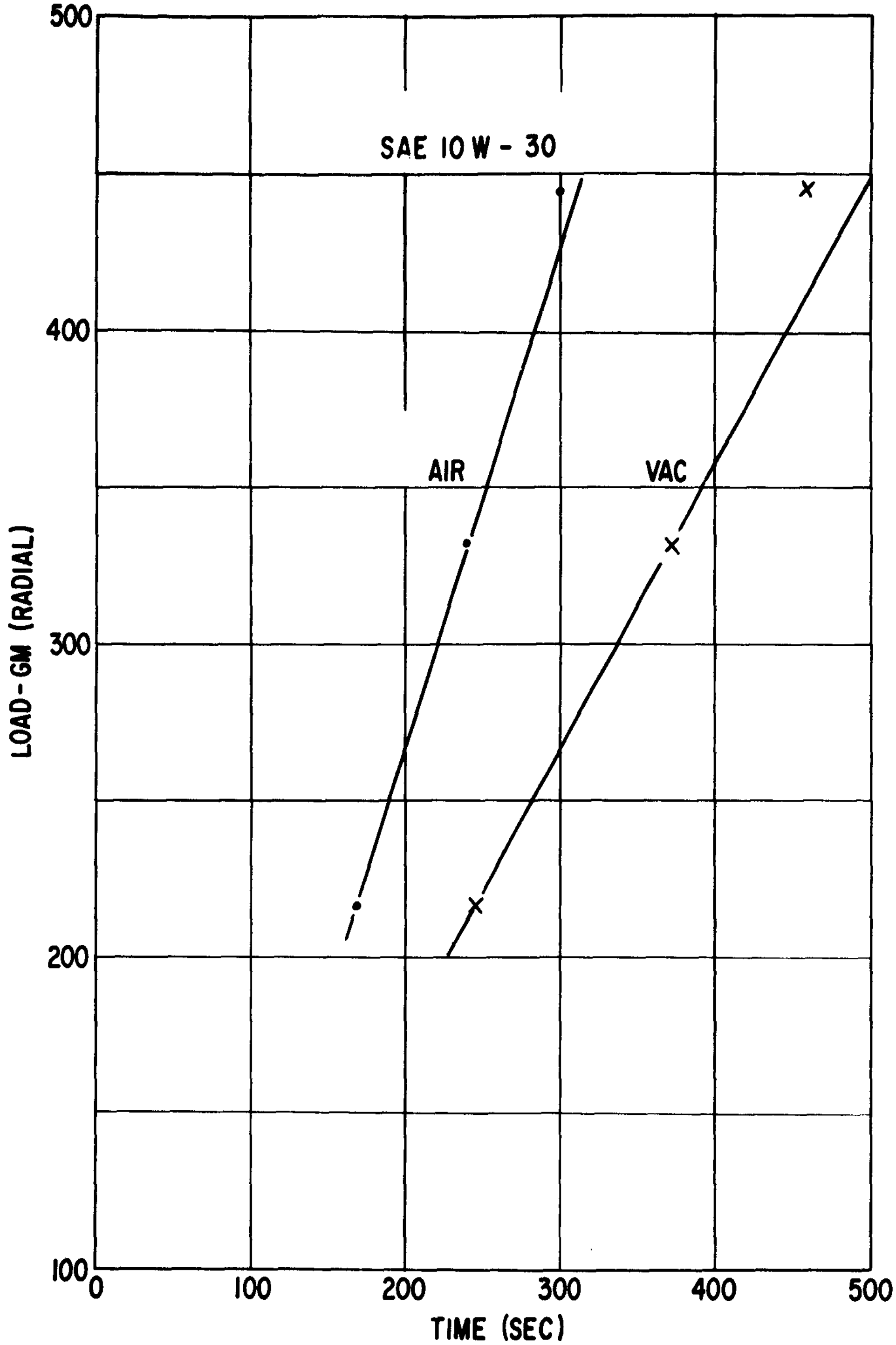


FIG 6 EFFECT OF LOAD ON TOTAL COASTDOWN TIME OF SAE IOW-30 PETROLEUM OIL IN AIR AND IN VACUUM

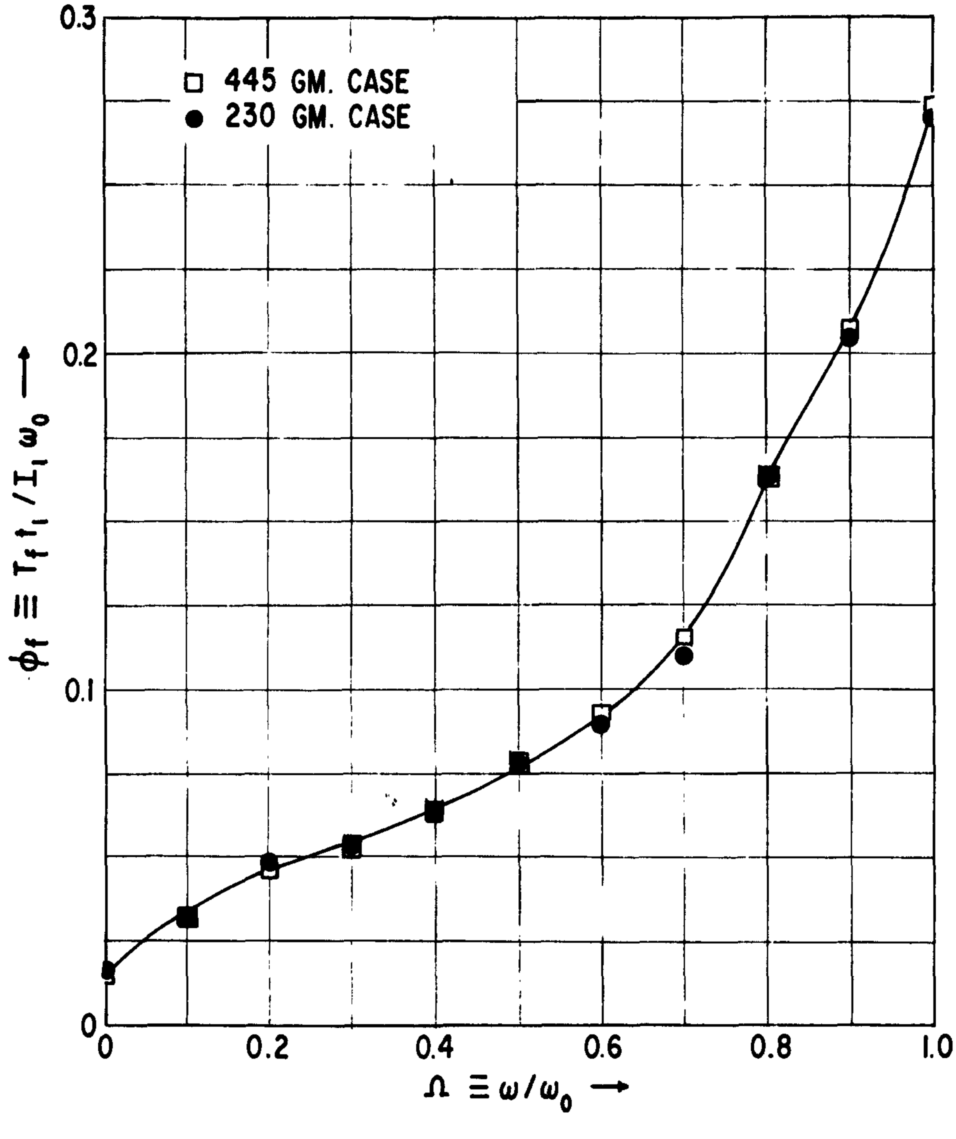


FIG. 7 DIMENSIONLESS FRICTION TORQUE AS A FUNCTION OF DIMENSIONLESS SPEED FOR SAE IOW-30 PETROLEUM

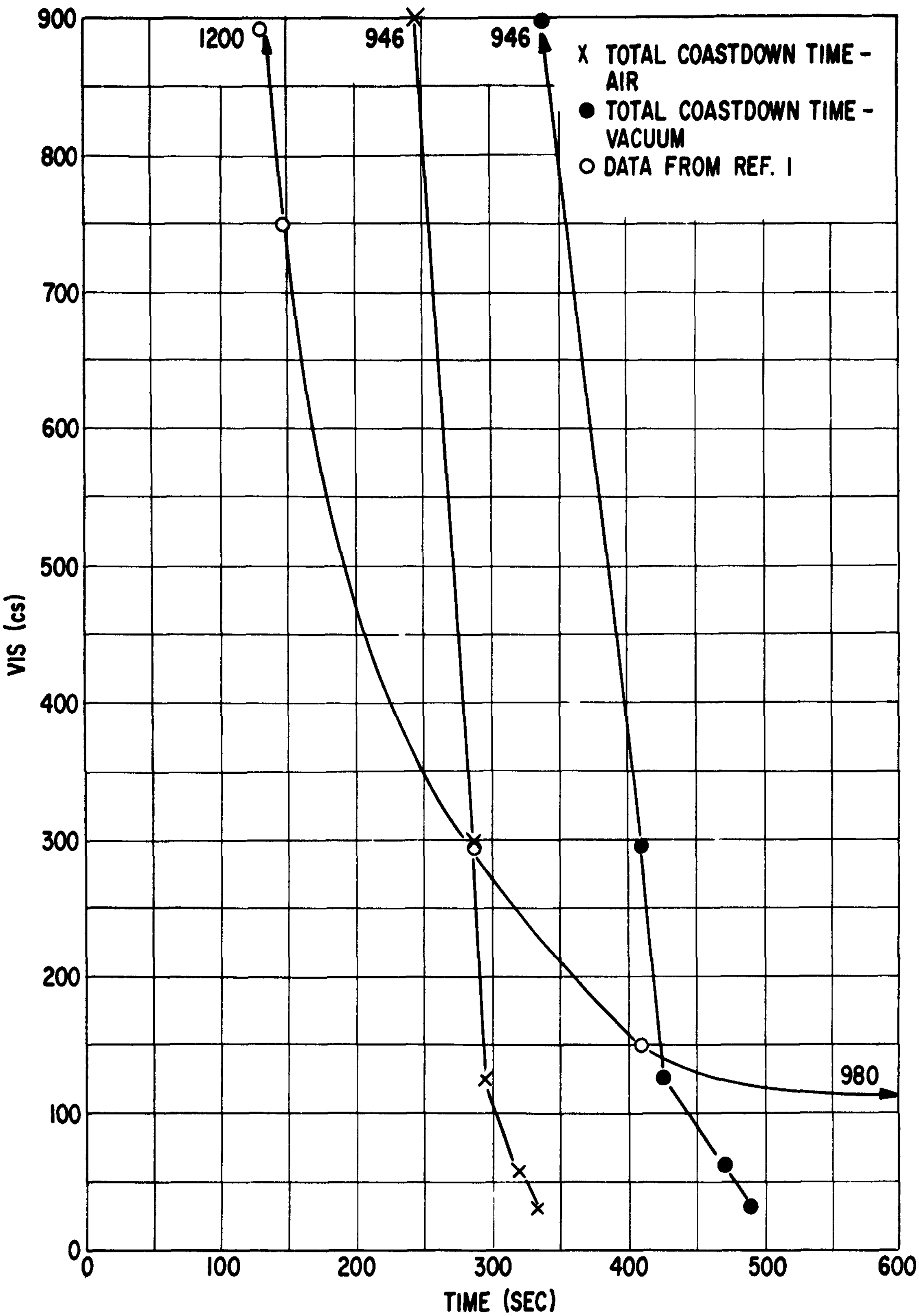


FIG. 8 EFFECT OF VISCOSITY ON TOTAL COASTDOWN TIME OF A HOMOLOGOUS SERIES OF UCON OILS

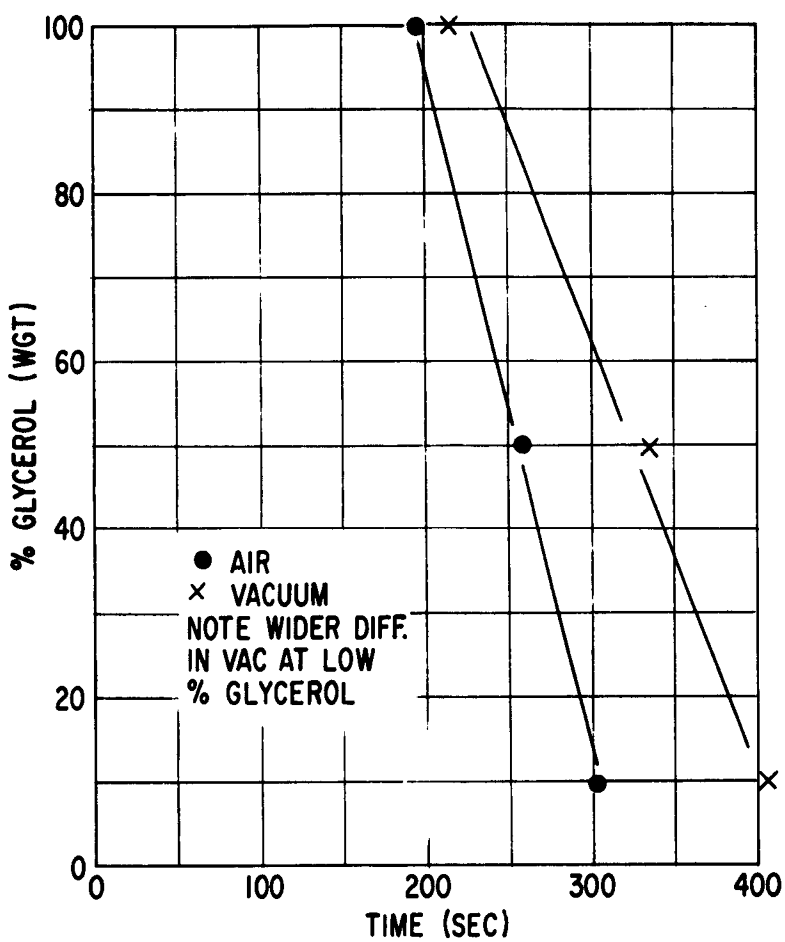


FIG. 9 EFFECT OF GLYCEROL CONCENTRATION ON TOTAL COASTDOWN TIME OF GLYCEROL-WATER SOLUTIONS IN AIR AND IN VACUUM

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